BUBBLE COALESCENCE IN MAGMAS Richard A Herd & Harry Pinkerton

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Summary: The most important factors governing the nature of volcanic eruptions are the primary volatile contents, the ways in which volatiles exsolve, and how the resulting bubbles grow and interact. In this contribution we assess the importance of bubble coalescence. The degree of coalescence in alkali basalts has been measured using Image Analysis techniques and it is suggested to be a process of considerable importance. Binary coalescence events occur every few minutes in basaltic melts with vesicularities greater than around 35%.

Introduction Several processes influence the bubble size distribution (BSD) in a solidified volcanic rock, *e.g.* nucleation, diffusional growth, decompressional growth, coalescence and loss by dissolution, ascent or fracturing. Sparks [1] described the major controls on the growth of bubbles in supersaturated melts, but did not incorporate the effect of bubble coalescence. Coalescence is important because it is a spontaneous process leading to a reduction in the free energy of the gas, and it has three major consequences: *Physical and rheological properties.* Coarsening of the mean bubble size affects the tensile strength, permeability and viscosity of a vesiculated magma, altering its behaviour during ascent and eruption. Binary coalescence in a foam halves its tensile strength and increases its permeability to gas flow by 60%. *Gas separation.* Coalescence facilitates the separation of gas from magma due to the improved collection of gas and the increased ascent velocity of bubbles. This is particularly important in shallow, long-lived magma bodies undergoing continuous degassing and influences eruption dynamics. High degrees of coalescence control the spasmodic style of Strombolian explosive activity [2-4]. *Volumetric changes.* In low pressure environments, significant gas expansion accompanies coalescence, increasing the vesicularity of lavas and bombs. The amount of inflation is obtained by considering the pressures inside bubbles in magmas. The internal pressure, P_b in a non-growing bubble is given by:

$$P_b = h\rho g + \frac{2\sigma}{r} + P_{atm}$$

The number of moles of gas is constant before and after coalescence, *i.e.*: $PV_n = nPV$, where n is the number of bubbles that coalesce and V_n is the volume of the resulting bubble, or specifically:

$$\left(h\rho g + \frac{2\sigma}{r_n} + P_{atm}\right)r_n^3 = n\left(h\rho g + \frac{2\sigma}{r} + P_{atm}\right)r^3$$

where r_n is the new bubble radius, r the initial radius, and the other symbols have their standard meanings. If the pressure generated due to surface tension (σ) is significant relative to the other pressure terms, then there is a noticeable net expansion of the new bubble. Solutions are given in Fig. 1 for coalescence on the surface of Earth and Mars for bubbles of 1 mm diameter. The expansion of the gas phase on Earth would be only 1.5%, but on Mars it is 16%.

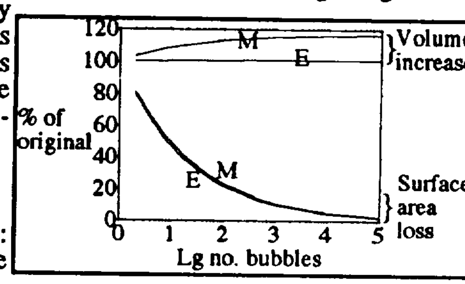

Fig. 1. Plot showing changes in volume of the gas phase and total surface area as a function of no. of bubbles, during coalescence on Earth (E) and Mars (M).

Unambiguous evidence of coalescence can be seen in samples when the common wall between two bubbles has failed and partially coalesced bubbles are observed. However, the septum of the common wall will retract due to surface tension, leaving a single, larger bubble with no evidence of coalescence. Consequently, visual inspection of the samples cannot be used to determine the e tent of coalescence. We have used image analysis techniques to model the degree (*i.e.* values of n) and rate of coalescence in vesiculated samples. The lower cooling rate of the interiors allows a greater time for vesiculation and interaction of bubbles, resulting in strong zonation with respect to vesicularity and bubble size, both increasing towards the centre of the sample. Bombs, lava crusts and aa blocks from Mt. Etna have been used in this study.

Methods Ten samples of alkali basalts were sawn perpendicular to their crusts. Vesicles on their polished surfaces were filled with a white matrix of alumina to produce a strong colour contrast between rock and vesicles. The samples were scanned using a Hewlett Packard ScanJet Plus at a resolution of 85 µm/pixel and the 8-bit images processed on a Macintosh IIci. Image analysis software (*NIH Image*) was used to measure raw properties (areas, perimeters, orientations and axial lengths) of bubble intersects on binary images. Stereological theory [5,6] was used to convert raw properties measured on 2-D images to the related properties of 3-D samples. These included bubble size analyses and morphological properties, *i.e.* bubble number density (N_v, the number of bubbles per unit volume), porosity (ϕ), mean radius (r) and specific surface area (S_v, surface area per unit volume). Models have been developed to follow the evolution of bubbles in related samples (related by, cooling time in a zoned sample, position in a lava flow, *etc.*). Vesiculation expands a melt and can be dominated by nucleation or diffusion. Coalescence, which reduces S_v but does not affect the value of ϕ, may be superimposed on these processes. Point A on Fig. 2 represents the vesicularity of a clot of magma erupted with a given ϕ and S_v. During protracted cooling, if sufficient volatiles are available for continued degassing, the sample could evolve along the nucleation, diffusion or coalescence paths. The final path taken is potentially a combination of all three processes.

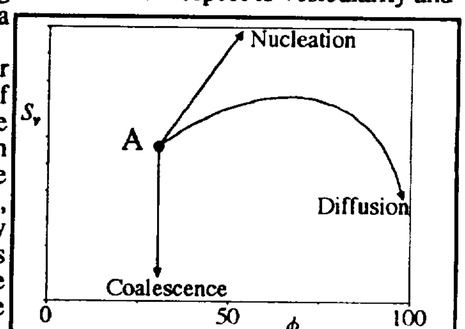

Fig. 2. Paths taken by a magma erupted at A depending upon the dominant vesiculation process on an S_v v. ϕ plot.

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The margins of each sample we have studied are dense relative to their interiors and they are assumed to represent the state of the melt on eruption (*i.e.* point A on Fig. 2). It is further assumed that the interiors have followed a growth path from this point. In order to evaluate the contribution of the three processes, growth curves have been fitted to the measurements made on the margins of each sample.

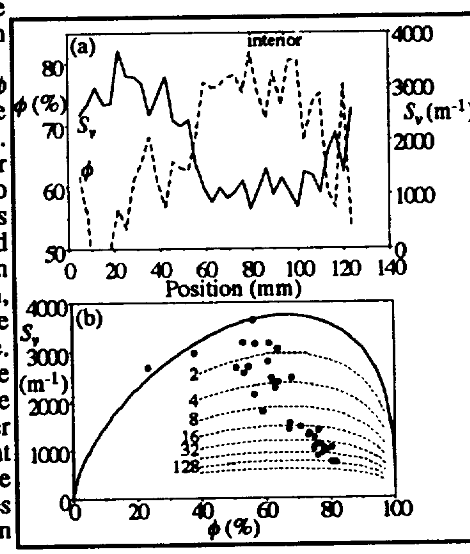

Fig. 3. (a) Profile of ϕ and S_v through RH/E8. Note that the inflated interior has the lowest S_v, (b) Plot of S_v against ϕ. Top curve is path taken for diffusion only, underlying curves indicate reduced S_v due to coalescence. The number of bubbles involved is shown to the left of each curve.

Results Results for sample RH/E8 are shown (Fig. 3) as a profile of ϕ and S_v as functions of position and then as S_v against ϕ to estimate the degree of coalescence by comparison with a diffusional growth curve. *Bombs and aa blocks.* All samples show an increase in ϕ as the interior of a sample is approached, with an equivalent fall in S_v. This is due to the combined effects of diffusional growth and coalescence. RH/E8 has been used to show how the number of coalescence events is calculated (Fig. 3b). A single binary coalescence event produces a 21% reduction in S_v. For RH/E8, the bubbles in the interior grew as a result of diffusion, taking ϕ from 50% to over 80% coupled with 6–7 binary coalescence events, giving an S_v which is 22% of that predicted by the growth curve. *Lava crusts.* Data obtained from lava crusts is complicated by the possibility of additional bubbles ascending from the hotter interior of the flow. One sample shows extensive coalescence. Bubbles in the upper part of its crust fit exactly on the growth curve; lower in the crust, at high porosities, coalescence has been extensive and the measurements are displaced below the growth curve. Our other lavas have low porosities (<30%) and show a positive correlation between ϕ and S_v as they are on the early part of a growth curve and few bubbles have interacted.

Discussion Field measurements [7] and theoretical studies (Kent, pers. comm) indicate that a 5 cm thick crust can form on the top of a basalt flow in about 30 min. In view of the small sample size, this has been taken as the maximum time for bubble growth and interaction after eruption, indicating binary coalescence events every few minutes. If magmatic foams can form at the tops of shallow magma chambers [8,9], their lifetimes should be carefully evaluated as the speed of coalescence suggested here would indicate collapse to dense melt and free gas in a few hours. This would result in free gas at the top of a chamber, overlying a zone of frothy melt undergoing coalescence and film drainage above melt whose vesicularity decreases with depth.

Aubele *et al.* [10] describe a model for the vesiculation of lavas, based on diffusional growth and ascent of bubbles. If their model was obeyed by all our samples, ϕ and S_v would both increase downwards at all values of ϕ. This is seen in our low porosity samples. At higher porosities, the effect of coalescence becomes significant reducing S_v. Walker [11] and Sahaigan *et al.* [12] observed significant bubble coalescence in basaltic flows. At porosities greater than 30–35%, the Aubele *et al.* model should be modified to include this effect.

Limitations of this study. It is stressed that this method underestimates both the degree and rate of coalescence because: (i) the samples are compared with the diffusion growth curve which predicts a minimum number of events compared to nucleation; and (ii) the cooling rates assume a dense rock equivalent. They do not include radiative heat loss across bubble walls or forced convective heat loss from the bombs during passage through the atmosphere. The models assume spherical geometry and so have limitations at high vesicularities, due to close packing. At all gas fractions a range of bubble sizes is observed, rather than a single size as modelled.

Conclusions We have put forward a simple method for measuring the degree of nucleation, diffusional growth and coalescence of bubbles in vesicular, volcanic rocks. The technique has been applied to a series of alkali basalts from which we conclude the following: (i) Bubble coalescence is detectable in vesicular rocks at porosities as low as 35%. Above this porosity, coalescence is extensive and S_v is inversely correlated with ϕ; (ii) Binary coalescence events occur on timescales of a few minutes, suggesting that basaltic foams will collapse and separate to melt + free gas in a few hours; and (iii) Given the degree of coalescence measured in our samples, products erupted into a low pressure atmosphere will suffer a marked expansion and increase in vesicularity solely due to coalescence of bubbles. Foams of more viscous magma will be longer-lived [8] but still undergo steady coalescence, which aids degassing. Coalescence is a general process that should be considered in the late stages of magmatic evolution when gas may coexist with the magma, and during the vesiculation history of lavas and pyroclastics.

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